

HARD PHOTODISINTEGRATION OF ^3He

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Abstract

Large angle photodisintegration of two nucleons from the ^3He nucleus is studied within the framework of the hard rescattering model (HRM). In the HRM the incoming photon is absorbed by one nucleon's valence quark that then undergoes a hard rescattering reaction with a valence quark from the second nucleon producing two nucleons emerging at large transverse momentum . Parameter free cross sections for pp and pn break up channels are calculated through the input of experimental cross sections on pp and pn elastic scattering. The calculated cross section for pp breakup and its predicted energy dependency are in good agreement with recent experimental data. Predictions on spectator momentum distributions and helicity transfer are also presented.

I. INTRODUCTION

Breakup of nucleon-nucleon (NN) systems at large energy and momentum transfer is an important tool in probing QCD descriptions of nuclear processes at this kinematic regime. In NN breakup, large NN center of mass energies where QCD degrees of freedom become evident, are reached with moderate beam energies in comparison with nucleon nucleon collisions. The simplest of these processes, the photodisintegration of the deuteron has been intensively studied through experiments at kinematics where the hadronic description is no longer applicable (see, e.g., Refs.[1],[2]). It has been observed that at 90° center of mass angle and beam energies of few GeV, the measured differential cross section scales in accordance with the constituent counting rule for exclusive processes [3], signaling the onset of quark degrees of freedom in the reaction.

Several QCD models of NN breakup have been developed in order to described features observed in the experimental data. Among these, models such as the reduced nuclear amplitude (RNA) approach [4], the quark gluon string (QGS) model [5], and the hard rescattering model (HRM) [6] rely on different approaches in dealing with the nonperturbative factors that enter the calculations. For the RNA approach, these factors are accounted for by introducing parameterizations of nucleon and nuclear form factors. The QGS model introduces a reggeization of the scattering amplitude, while through the HRM, breakup cross sections are calculated through the input of experimental data of cross sections of the corresponding nucleon nucleon elastic scattering process.

Calculations of cross sections of deuteron photodisintegration in the RNA and the QGS approaches require a normalization to the data. In contrast, in the HRM these cross sections are obtained without the need of a normalization parameter. In order to further test the validity of these competing approaches, it was proposed to extend photodisintegration studies to the breakup of proton proton (pp) and proton neutron (pn) systems in the ^3He nucleus [7]. For these reactions, numerical predictions for the cross section differ considerably from one approach to another. Recent experimental data [8] shows a better agreement with HRM calculations[9].

Additional constrains on the analysis of NN breakup are set in ^3He photodisintegration by studying observables such as the spectator momentum distributions and polarization transfer asymmetries. Features on these observables predicted here within the HRM are expected to be put to the test in future experimental analysis.

II. HRM OF ^3He PHOTODISINTEGRATION

Fig.1 illustrates the HRM picture of the breakup of a NN pair in ^3He photodisintegration. It differs graphically from that of the deuteron breakup by the presence of a spectator nucleon. In Fig.1, by absorbing the incoming photon, a valence quark is knocked out from one of the nucleons in the initial NN system. This quark then re scatters off a valence quark from the second nucleon. Both quarks then recombine with the spectators systems to form two nucleons with large transverse momentum in the final state.

Within the HRM, The scattering amplitude is obtained using Feynman rules on the diagram in Fig.1. The only calculable terms are the QED vertex corresponding to the photon absorption by the valence quark and the component of the nuclear wave function represented by the ^3He vertex. The scattering amplitude is then reduced to the form in

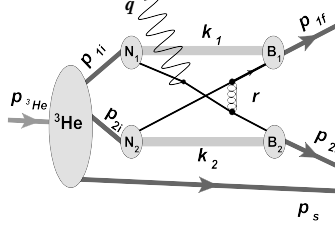


FIG. 1: ^3He photodisintegration according to the HRM

Eq.(1) through two main assumptions (see Ref. [9] for details). First, by working in a $q^+ = 0$ reference frame, we approximate the struck nucleon's propagator to its on shell component. Second, we assume that the nucleons in the NN system have an equal share of the NN light cone momentum, which maximizes the nuclear wave function. The result as shown in Eq.(1) is a convolution of a nuclear wave function $\Psi_{^3\text{He}}$ and the scattering amplitude T of a kinematically corresponding NN elastic scattering reaction.

$$\begin{aligned}
\langle \lambda_{1f}, \lambda_{2f}, \lambda_s | \mathcal{M} | \lambda_\gamma, \lambda_A \rangle = & ie[\lambda_\gamma] \times \\
& \left\{ \sum_{i \in N_1} \sum_{\lambda_{2i}} \int \frac{Q_i^{N_1}}{\sqrt{2s'}} \langle \lambda_{2f}; \lambda_{1f} | T_{NN,i}^{QI}(s, t_N) | \lambda_\gamma; \lambda_{2i} \rangle \right. \\
& \quad \Psi_{^3\text{He}}^{\lambda_A}(p_1, \lambda_\gamma; p_2, \lambda_{2i}; p_s, \lambda_s) \frac{d^2 p_\perp}{(2\pi)^2} \\
& + \sum_{i \in N_2} \sum_{\lambda_{1i}} \int \frac{Q_i^{N_2}}{\sqrt{2s'}} \langle \lambda_{2f}; \lambda_{1f} | T_{NN,i}^{QI}(s, t_N) | \lambda_{1i}; \lambda_\gamma \rangle \\
& \quad \left. \Psi_{^3\text{He}}^{\lambda_A}(p_1, \lambda_{1i}; p_2, \lambda_\gamma; p_s, \lambda_s) \frac{d^2 p_\perp}{(2\pi)^2} \right\}, \tag{1}
\end{aligned}$$

where $\lambda_1, \lambda_2, \lambda_s$ are the helicities of the nucleons from ^3He . $\lambda_A, \lambda_\gamma$ are the helicities of the nucleus and of the incoming photon respectively, and Q_i^N is the charge in e units of the quark struck by the photon. A further reduction is achieved if $-t_N \gg m_N^2$. Under this condition, the matrix elements of T can be factored out of the p_\perp integral.

Using the following notation for the independent helicity amplitudes in NN elastic scattering,

$$\begin{aligned}
\langle +, + | T | +, + \rangle &= \phi_1 \\
\langle +, - | T | +, - \rangle &= \phi_3 \\
\langle -, + | T | +, - \rangle &= \phi_4 \\
\langle -, - | T | +, + \rangle &= \phi_2 \\
\langle -, + | T | +, + \rangle &= \phi_5,
\end{aligned} \tag{2}$$

and from explicitly working the matrix elements in Eq.(1), we can write the averaged of the squared of the scattering amplitudes \mathcal{M} as follows,

$$|\bar{\mathcal{M}}|^2 = \frac{1}{2} \frac{1}{3} \frac{e^2}{2s'} \left[S_{12} \left\{ |(\hat{Q}^{N_1} + \hat{Q}^{N_2})\phi_1|^2 + |(\hat{Q}^{N_1} + \hat{Q}^{N_2})\phi_2|^2 \right\} \right]$$

$$\begin{aligned}
& + S_{34} \left\{ |\hat{Q}^{N_1} \phi_3 + \hat{Q}^{N_2} \phi_4|^2 + |\hat{Q}^{N_1} \phi_4 + \hat{Q}^{N_2} \phi_3|^2 \right\} \\
& + 2S_0 |(\hat{Q}^{N_1} + \hat{Q}^{N_2}) \phi_5|^2,
\end{aligned} \tag{3}$$

where the light-cone spectral functions of the ${}^3\text{He}$ nucleus are defined as follows:

$$\begin{aligned}
S_{12} &= N_{NN} \sum_{(\lambda_1=\lambda_2=-\frac{1}{2})}^{\frac{1}{2}} \sum_{(\lambda_s=-\frac{1}{2})}^{\frac{1}{2}} \left| \int \Psi_{\frac{1}{2}\text{He}}^{\frac{1}{2}}(p_1, \lambda_1; p_2, \lambda_2; p_s, \lambda_s) \frac{d^2 p_{\perp}}{(2\pi)^2} \right|^2, \\
S_{34} &= N_{NN} \sum_{(\lambda_1=-\lambda_2=-\frac{1}{2})}^{\frac{1}{2}} \sum_{(\lambda_s=-\frac{1}{2})}^{\frac{1}{2}} \left| \int \Psi_{\frac{1}{2}\text{He}}^{\frac{1}{2}}(p_1, \lambda_1; p_2, \lambda_2; p_s, \lambda_s) \frac{d^2 p_{\perp}}{(2\pi)^2} \right|^2, \\
S_0 &= S_{12} + S_{34},
\end{aligned} \tag{4}$$

and the charge factors \hat{Q}^N account for all possible quark photon interactions contributing to the reaction's amplitude. For two nucleon breakup in ${}^3\text{He}$, the unpolarized cross section is given by

$$\frac{d\sigma}{dt d^3 p_s / (2E_s (2\pi)^3)} = \frac{|\bar{\mathcal{M}}|^2}{16\pi(s - M_A^2)(s_{NN} - M_{NN}^2)} \tag{5}$$

where $s = (q + p_A)^2$, and $s_{NN} = (q + p_{NN})^2$. Then according to Eq.(3), the cross section in Eq.(5) can be computed from the knowledge of the ϕ scattering amplitudes, and of the charge factors \hat{Q} . Because there is not enough experimental data in polarized NN scattering to extract the helicity amplitudes ϕ , Eq.(5) can instead be computed through general assumptions regarding these amplitudes. This is further discussed in the coming sections.

Alternatively, the ϕ amplitudes can be modeled according to a NN scattering mechanism. Experiments have demonstrated the dominance of the quark interchange mechanism (QIM) in hard exclusive reactions between baryons of common quark flavors such as pp and pn elastic scattering [10]. Within a (QIM) approach, the ϕ amplitudes are obtained by assuming a symmetry structure of the valence quark wave functions of the interacting baryons (see e.g., Refs.[11]). A starting point is using SU(6) symmetric wave functions [11], but it has been suggested that a diquark model better describes general features in pn elastic scattering such as its strength relative to pp scattering, and the asymmetry observed in its angular distributions (see, e.g., Ref.[12]).

Finally, an important feature of the HRM is that at large values of s and $-t$ it predicts an energy distribution of Eq.(5) in accordance with the constituent counting rule [3]. That is $\frac{d\sigma}{dt} \sim s^{-11}$ [6],[7],[9], which comes from the s^{-4} dependence of the ϕ amplitudes entering Eq.(3). This behavior has already been observed in deuteron photodisintegration [1],[2], and in recent experiments on pp breakup in ${}^3\text{He}$ [8].

A. pn and pp breakup

As mentioned in the previous section $\frac{d\sigma}{dt}$ in Eq.(5) can be computed through general assumptions on pn and pp elastic scattering.

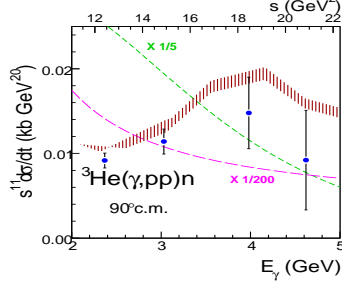


FIG. 2: Cross section data for pp breakup in ${}^3\text{He}$ photodisintegration at 90° c.m. angle of the $\gamma + pp$ system [8]. (Dashed) QGS prediction times 1/5. (Long dashed) RNA prediction times 1/200. (Shaded) HRM prediction.

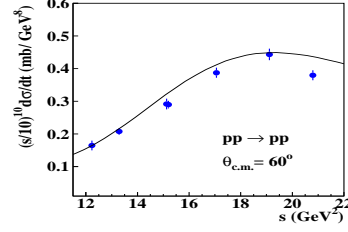


FIG. 3: pp elastic scattering data at 60° of center of mass angle of scattering. These data is used in Eq.(7) to calculate the HRM cross section of pp breakup shown in Fig.2.

1. $\gamma^3\text{He} \rightarrow pn + p$

In pn breakup, pn scattering amplitudes ϕ enter Eq.(3). Using that for hard pn elastic scattering $\phi_3 \sim \phi_4$ (see, e.g., Ref. [13]), and that at low transverse momentum $p_\perp \ll m_N$, $\Psi_{3\text{He}} \approx \sqrt{2}(2\pi)^3 m_N \Psi_{3\text{He,NR}}$ [14], the cross section of pn breakup can be approximated to a simple product of a spectral function and a cross section of a kinematically corresponding pn elastic reaction,

$$\begin{aligned} \frac{d\sigma^{\gamma^3\text{He} \rightarrow (pn)p}}{dt \frac{d^3 p_s}{E_s}} &= \alpha Q_{F,pn}^2 16\pi^4 \frac{S_{0,NR}^{pn}(\alpha_c = \frac{1}{2}, \vec{p}_s)}{2} \frac{s_{NN}(s_{NN} - 4m_N^2)}{(s')(s - M_{3\text{He}}^2)} \\ &\times \frac{d\sigma^{pn \rightarrow pn}(s_{NN}, t_N)}{dt_N}, \end{aligned} \quad (6)$$

where $Q_F = 1/3$, $\alpha = 1/137$ and $s' = s_{NN} - M_{NN}^2$.

2. $\gamma^3\text{He} \rightarrow pp + n$

At large center of mass angle of scattering in pp elastic scattering, it follows from Pauli's principle that $\phi_4 \sim -\phi_3$ (see, e.g., Ref.[15]). Also, assuming that the S states dominates the ground state nuclear wave function, from the exclusion principle, the probability of two protons having the same helicity is negligible. Therefore, $S_{12} \ll S_{34}$. These assumptions allow to write the cross section for pp breakup in ${}^3\text{He}$ photodisintegration as follows:

$$\begin{aligned} \frac{d\sigma^{\gamma^3\text{He} \rightarrow (pp)n}}{dt \frac{d^3 p_s}{E_s}} &= \alpha Q_{F,pp}^2 16\pi^4 S_{34}^{pp}(\alpha = \frac{1}{2}, \vec{p}_s) \frac{s_{NN}(s_{NN} - 4m_N^2)}{s'(s - M_{3\text{He}}^2)} \\ &\times \frac{2\beta^2}{1 + 2C^2} \frac{d\sigma^{pp \rightarrow pp}(s_{NN}, t_N)}{dt}, \end{aligned} \quad (7)$$

where, $C^2 = (\phi_3^2/\phi_1^2) \approx (\phi_4^2/\phi_1^2)$, $\beta = (|\phi_3| - |\phi_4|)/|\phi_1|$ and $Q_F=5/3$. Because the pp breakup cross section is proportional to β and having that $|\phi_4| \sim |\phi_3|$, we predict a large suppression of the pp breakup relative to the pn breakup case.

Eq.(7) shows that just as in the pn breakup case, the pp breakup cross section is proportional to the cross section of the corresponding pp elastic scattering. This is illustrated in Figs. 2 and 3 that show that the shape of the scaled energy distribution for pp breakup mimics that of the scaled energy distribution for the corresponding pp elastic scattering. Fig.2 also shows that the HRM calculation is in very good agreement with the experimental data.

B. Spectator momentum distributions

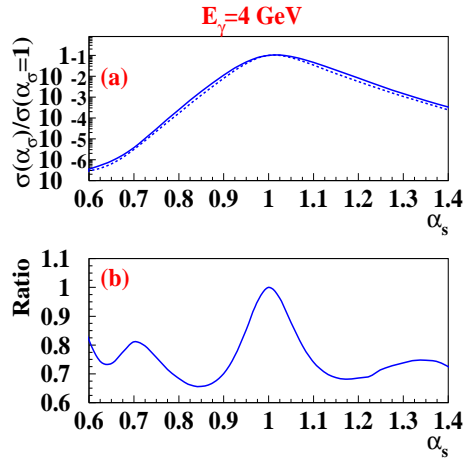


FIG. 4: (a) pp breakup (solid line) and pn breakup (dashed line) s^{11} -weighted HRM cross sections as functions of the spectator nucleon's light cone momentum fraction (α_s) and normalized to their values at $\alpha_s = 1$. (b) Ratio (R) of the pn to pp breakup HRM cross sections normalized to its value at $\alpha_s = 1$.

Additional observables can be extracted from ${}^3\text{He}$ photodisintegration in order to test or constrain the validity of the HRM. We consider for instance the spectator momentum distributions plotted in Fig.4. In Fig.4a we noted that the asymmetry in both distributions around $\alpha_s = 1$ is due to the s^{-11} dependence of both cross sections. As less energy is taken by the spectator nucleon, more energy is taken by the NN system, hence the sharper drop towards $\alpha_s = 0$. The broader pp breakup distribution in Fig.4a, as well as the sharp drop of R around $\alpha_s = 1$ are due to the suppression of the S_{12}^{pp} spectral function in the low NN momentum component of the nuclear wave function.

C. Polarization transfer observables

Another observable of interest is related to the effectiveness with which the incoming photon transfers its helicity to an outgoing proton. This is measured through the asymmetry

$C_{z'}$ (see, e.g., [9]) that in the HRM takes the form

$$C_{z'} = \frac{(|\phi_1|^2 - |\phi_2|^2)S^{12} + (|\phi_3|^2 - |\phi_4|^2)S_{34}}{2|\phi_5|^2 S_0 + (|\phi_1|^2 + |\phi_2|^2)S_{12} + (|\phi_3|^2 + |\phi_4|^2)S_{34}}, \quad (8)$$

Noting that for pp breakup $S_{12} \approx 0$ and $\phi_4 \approx -\phi_3$, we have that $C_{z'}^{pp} \approx 0$, while for pn breakup $C_{z'}^{pn} \approx 2/3$.

III. SUMMARY

We studied the hard breakup of a nucleon pair in hard a ^3He nucleus by introducing quark degrees of freedom through the hard rescattering model (HRM). Cross sections for proton neutron pn and proton proton breakup are calculated in the (HRM) without the need for introducing a parameter to normalize to data. The obtained cross section for pp breakup shows good agreement with recent experimental data. We also predict distinctive spectator momentum distributions for both pp and pn breakup, and a cancellation of the $C_{z'}$ asymmetry in the pp breakup channel. Mounting evidence in favor of the rescattering picture of breakup processes motivates an extension of these study to different baryonic channels such as $\Delta\Delta$ -isobar in deuteron breakup (see, e.g., Ref.[16]) for which experiments are already being proposed.

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